

Dynamical CP violation in the early Universe

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Abstract

Following earlier ideas of Dolgov, we show that the asymmetrical dynamical evolution of fields in the early Universe provides a new source for CP violation. This can lead to baryogenesis without any additional CP-violating interactions. The magnitude of this CP violation is time-dependent. In particular, it vanishes (or is very small) in the late Universe after the fields have relaxed (or are in their final approach) to their vacuum values. We provide an explicit example in which our mechanism is realized.

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1. Introducing dynamical CP violation

The observed CP violation in our Universe has so far only been measured in the K -meson and B -meson sectors (see, e.g., Ref. [1] for recent reviews on the status of CP violation), and is generally believed to be due to CP-violating phases in the quark mass matrix (the Kobayashi–Maskawa (KM) mechanism [2]). CP violation is one of the key criteria required in order to generate the observed baryon–antibaryon asymmetry of the Universe starting with symmetric initial conditions. However, because of the smallness of the

quark masses, CP violation from the KM mechanism is highly suppressed for processes relevant to baryogenesis [3], and all successful mechanisms of baryogenesis studied to date postulate new CP-violating couplings arising in new physics beyond the Standard Model (for recent reviews of baryogenesis see, e.g., Ref. [4]). On the other hand, the three required criteria for baryogenesis [5], namely the existence of baryon number violating processes, CP violation, and out-of-equilibrium dynamics, all are present in the Standard Model. Thus, one may wonder if it might not be possible to realize successful baryogenesis without introducing new sources of baryon number violation and new couplings which explicitly break CP (for attempts in this direction see Refs. [6,7]).

In this Letter we point out that within early Universe cosmology there exists a natural source for CP

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violation. This can be used to obtain the enhanced CP violation required to make it possible to generate a large enough baryon asymmetry in the context of Standard Model baryogenesis. The key observation, already made some time ago by Dolgov [8], is that in a model which contains several complex scalar fields, initial conditions in a given small region of the early Universe will typically generate an asymmetry in the phases of the fields. This asymmetry can be initially induced by thermal or quantum excitations of the fields about the symmetric state. A stage of inflation in the early Universe will lead to an exponential increase in the wavelength of the local fluctuation regions, thus rendering our present Hubble patch of the Universe asymmetric.

If the asymmetry in the phases of the fields can be connected with a CP asymmetry, then it is possible to realize a scenario in which the Lagrangian is CP symmetric (modulo the CP-violating phases in the quark mass matrix of the Standard Model), but the phase asymmetry of the fields in the early Universe leads to (possibly large) CP violation during the period when the fields are relaxing to their ground state values (which we assume are symmetric).¹ Thus, a specific feature of our mechanism is that the magnitude of CP violation is time dependent. Large CP violation in the early Universe in sectors other than the KM mass matrix could thus be compatible with the absence of such effects today. The largeness of CP violation in the early Universe could then enhance the effectiveness of various baryogenesis mechanisms which have been proposed. For example, if the scalar fields are rolling at times corresponding to the electroweak phase transition, the effectiveness of electroweak baryogenesis could be significantly enhanced, maybe rendering it possible to obtain baryogenesis with Standard Model physics which is effective enough to generate the observed baryon to entropy ratio (see Ref. [15] for an interesting but unrelated mechanism which can in-

crease the efficiency of CP violation in the early Universe).²

The idea that CP violation might be large in the early Universe due to charge-asymmetric initial conditions is due to Dolgov [8], who introduced the term *stochastic breaking of charge symmetry* for it. It can be viewed as the realization of *spontaneous CP violation* [18] during a period in the early Universe. In the following, we develop this idea further. We introduce a toy model to demonstrate the viability of the mechanism. We then discuss the specific processes which in our toy model can generate a net CP asymmetry among the particle excitations of the fields, and demonstrate that it is possible to transfer this asymmetry to a net lepton number (which in turn can be transferred to a net baryon number by local thermal equilibration). Note that phases in multi-Higgs systems have also recently been invoked [19] as a way of generating the CP asymmetry in the early Universe necessary to see resonantly-amplified baryogenesis.

2. CP violation in the scalar sector

We begin by introducing a toy model containing two complex scalar fields ϕ_+ and ϕ_- . The fields are taken here to be electrically neutral (the case of electrically charged scalar fields will be analyzed in a separate publication [20]). The scalar potential of the model is taken to be

$$V(\phi_+, \phi_-) = \sum_{i=+,-} m_i^2 \phi_i^\dagger \phi_i + V_4(\phi_+, \phi_-), \quad (2.1)$$

where it is assumed that $m_+ > 2m_-$, and

$$V_4(\phi_+, \phi_-) = g \phi_-^\dagger \phi_-^\dagger \phi_- \phi_+ + \text{h.c.} \quad (2.2)$$

The Lagrangian is taken to be CP-conserving, so that g is real.

If the field initial conditions are asymmetric, as is expected in cosmology, we now show that the above scalar field interactions can generate a net

¹ With respect to the use of rolling scalar fields, our scenario has a certain analogy with the Affleck–Dine (AD) mechanism [9]. However, while the AD mechanism involves new scalar fields carrying baryonic charge and generating a net baryon number, our scalar fields do not involve new baryon-number-violating processes. Note that rolling scalar fields are also used in inflationary baryogenesis scenarios [10–14]. Once again, in these scenarios the Lagrangian contains new CP- or baryon-number-violating interactions.

² Note that the scalar fields can be identified with moduli fields in higher-dimensional compactifications (see Ref. [16] for a review), in particular the breathing and the squashing modes which can also effect symmetry-breaking transitions in gauge theories as they are evolving in time [17].

CP asymmetry among the local field excitations. We will assume that the cosmological initial conditions provide a phase asymmetry in the two scalar fields ϕ_+ and ϕ_- . To be specific, we assume that the initial value of ϕ_- is real, but the initial value of ϕ_+ has a phase α . As we will see, this yields the required weak phase necessary in order to generate a net CP asymmetry.

Inflationary cosmology [21] provides a ready mechanism to produce the kind of field initial conditions we require.³ Assume that the masses m_+ and m_- are light compared to the Hubble expansion rate H during inflation. Inflation will exponentially red-shift the wavelength of quantum field fluctuations in the two scalar fields ϕ_+ and ϕ_- . Since the motion of the fields is highly over-damped, the field fluctuation amplitude \mathcal{A} , which for quantum vacuum fluctuations will be of order H [22,23] and therefore large in comparison with the scales of Standard Model physics, will hardly decrease (if the initial perturbations are due to other than quantum vacuum fluctuations, the field amplitudes will be even larger). Thus, at the end of inflation, the fields ϕ_+ and ϕ_- will have obtained components $\phi_+^{(0)}$ and $\phi_-^{(0)}$ which are homogeneous on the scale of the present Hubble radius and whose amplitudes are large at late times. In general, there will be a relative phase difference α between the two fields. Once the Hubble rate H drops below the value of the mass m_i , the quasi-homogeneous component of the field ϕ_i ($i = +, -$) will begin to relax towards its vacuum value $\phi_i = 0$. The calculations we perform below make use of an approximation which is only valid in the later stages of the relaxation of the scalar fields, namely when the fields have decreased to values smaller than the masses ($|\phi_i| < m_-$ for $i = +, -$). However, CP violation is taking place throughout the relaxation process.

It is clear that our cosmological initial conditions contain an asymmetry in the weak phases of the fields. However, we must show that this phase asymmetry

can be transformed into a CP asymmetry in the localized excitations of the field (the field quanta) which are produced during the relaxation process. In the following we will also show that an asymmetry in the fermion sector is generated. In this way, the asymmetry survives even after the two scalar fields have relaxed to their ground state in which (by assumption) there is no residual weak CP-violating phase.

Before doing this, it is useful to first review the basic formalism for establishing a CP asymmetry. In general, one can parameterize the transition matrix element M corresponding to a particular decay as

$$M = A + \zeta B, \quad (2.3)$$

where ζ , A and B are complex numbers such that under a CP transformation we have $A \leftrightarrow A$, $B \leftrightarrow B$ and $\zeta \rightarrow \zeta^*$. The probability difference between the process and its CP-conjugate process can then easily be worked out, and the result determines the resulting CP asymmetry A_{CP} :

$$A_{CP} = C(|M|^2 - |\bar{M}|^2) = -2C \operatorname{Im}(\zeta) \cdot \operatorname{Im}(AB^*), \quad (2.4)$$

with C being a constant.

Clearly, in order to obtain net CP violation, one needs both a non-vanishing *strong phase* difference $\operatorname{Im}(AB^*) \neq 0$ and a *weak phase* $\operatorname{Im}(\zeta) \neq 0$. In our scenario, the weak phase is given by the relative phase in the initial displacement of the fields from their symmetric values, whereas the strong phase is obtained in the usual way by making use of a radiative process such as a self-energy correction or a vertex correction graph.

With this formalism in hand, we can now show that the asymmetric initial conditions do indeed lead to a CP asymmetry in the fields. Because of these non-zero initial conditions, we must consider field fluctuations about these values:

$$\phi'_- = \phi_- - c_-, \quad \phi'_+ = \phi_+ - c_+ e^{i\alpha}, \quad (2.5)$$

where c_- and c_+ are real constants. (Note that c_{\pm} actually vary with time, but our analysis is performed at a given instant. A priori, even α can be time dependent. For our mechanism to work we require it to be varying slowly (if at all) so that the CP-violation effects can add coherently.) These relations can be inverted and inserted into the scalar potential

³ Although we discuss the origin of the weak phase difference and of the excitation of the scalar fields in the context of inflationary cosmology, the basic mechanism does not depend on having a period of inflation. In the context of any cosmological scenario with a hot initial phase, one would expect all fields to be excited, and relative phases to be generated. Inflation provides a natural mechanism for producing homogeneous initial conditions within our Hubble patch.

of Eq. (2.1). Expanding the quartic term of Eq. (2.2), one finds both quadratic and cubic terms. (There are other terms, but they are not relevant to our analysis.) The quadratic terms contribute to the mass matrix. However, if we make the simplifying assumption (valid in the later stages of the relaxation of the scalar fields) that $c_{+,-} \ll m_{+,-}$, then the mass corrections due to the initial conditions are negligible, and ϕ'_i are still mass eigenstates. (Note that this assumption is not absolutely necessary: it is possible to diagonalize the mass matrix and work with the new mass eigenstates, but this does not change our conclusions.) We will henceforth drop the primes.

The cubic terms generated by the initial conditions, which we denote as V_3 , have the following form:

$$V_3 = g[c_+ e^{i\alpha} \phi_-^\dagger \phi_-^\dagger \phi_- + c_- \phi_-^\dagger \phi_-^\dagger \phi_+ + 2c_- \phi_-^\dagger \phi_- \phi_+] + \text{h.c.} \quad (2.6)$$

These couplings can contribute to two-body decays of the fields, which can be treated analogously to how the decay of the inflaton field was initially analyzed perturbatively [10,24].⁴ Since $m_+ > 2m_-$, the only possible decay is of a ϕ_+ quantum to two ϕ_- quanta. We need to show that the decay produces a net CP asymmetry among the produced quanta.

Consider the decay $\phi_+ \rightarrow \phi_- \phi_-$. This process receives a tree and several loop contributions, with relative weak and strong phases. For the purposes of demonstration, we will consider only one of the diagrams which contributes at one loop (Fig. 1). (There are other loops of this type, as well as a vertex renormalization graph.) The interference between these diagrams yields the desired CP violation, and leads to a rate difference between $\phi_+ \rightarrow \phi_- \phi_-$ and $\phi_+^\dagger \rightarrow \phi_-^\dagger \phi_-^\dagger$.

One can see how this comes about as follows. Using the couplings in (2.6), we see that the tree and loop diagrams are proportional to $c_- g$ and $2c_- c_+^2 g^3 \times \exp(2i\alpha)$, respectively, and therefore have a relative weak phase. The loop diagram also has a strong phase. Because the decay $\phi_+ \rightarrow \phi_- \phi_-$ is kinematically permitted, the loop transition amplitude contains an absorptive part coming from the $i\epsilon$ piece in the prop-

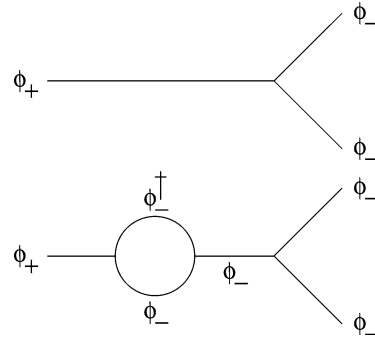


Fig. 1. Feynman diagrams of the tree and loop processes considered here.

agators. Thus, we immediately see that the transition matrix element for Fig. 1 will be of the necessary form [Eq. (2.3)] to obtain net CP violation in the final state. Specifically,

$$A_{\text{CP}} \sim \text{Im}(\zeta) \sim \sin 2\alpha. \quad (2.7)$$

We therefore see explicitly that A_{CP} is non-zero only if $\alpha \neq 0$. Thus, the phase α in the initial conditions is directly responsible for the net CP asymmetry.

Note that we should also pay attention to the decay $\phi_+^\dagger \rightarrow \phi_- \phi_-$. Even if there is a CP asymmetry between $\phi_+ \rightarrow \phi_- \phi_-$ and $\phi_+^\dagger \rightarrow \phi_-^\dagger \phi_-^\dagger$, it could potentially be cancelled by another CP asymmetry between $\phi_+^\dagger \rightarrow \phi_- \phi_-$ and $\phi_+ \rightarrow \phi_-^\dagger \phi_-^\dagger$. However, since all triple-scalar couplings can be different, it is not hard to ensure that this does not arise. Indeed, our choice of V_3 achieves this: since there is no $\phi_-^\dagger \phi_-^\dagger \phi_+^\dagger$ term, the decay $\phi_+^\dagger \rightarrow \phi_- \phi_-$ cannot occur at tree level.

3. Induced lepton and baryon asymmetry

Above, we demonstrated that the initial phase asymmetry can be converted to a CP-violating rate asymmetry in the scalar sector. The next necessary step is to show how to transfer this to the fermion sector. Given that the complex scalar fields ϕ_+ and ϕ_- are neutral, only a lepton asymmetry can be generated (through their couplings to neutrinos). This then induces a net baryon asymmetry via thermal equilibration. Thus, our mechanism can be a source for the standard leptogenesis scenario (see Ref. [27]

⁴ However, see Refs. [25,26] for a more efficient decay mechanism making use of a parametric resonance instability which occurs if the homogeneous field is oscillating.

for the original reference and e.g. Ref. [28] for a recent review of leptogenesis). However, special to our scenario is the fact that leptogenesis can be driven by either by Dirac or by Majorana fermions (not just by Majorana fermions as in the standard leptogenesis scenario). (Note: if the scalar fields are charged, then their decay can directly produce a baryon asymmetry (in this case the analogy with the Affleck–Dine mechanism [9] would be greater).)

We first discuss the case where the fermions are Dirac particles. The relevant Yukawa interaction is

$$Y = \sum_{a,b} \bar{\psi}_L^a (\phi_+ Y_{ab}^1 + \phi_- Y_{ab}^2) \psi_R^b + \text{h.c.}, \quad (3.1)$$

where the Y_{ab}^i are the Yukawa coupling matrices, and the indices a and b run over the neutrinos. The decay processes of interest are $\phi_- \rightarrow \bar{\psi}_L \psi_R$ and $\phi_-^\dagger \rightarrow \bar{\psi}_R \psi_L$. Since we have unequal numbers of ϕ_- and ϕ_-^\dagger quanta [Eq. (2.7)], the decays of the scalars will lead to an unequal number of left- and right-handed Dirac neutrinos. This asymmetry has magnitude $A^\nu \sim |Y|^2 A_{\text{CP}}$, and can successfully generate a baryon asymmetry for very small Yukawa couplings [29]. There are, however, a number of qualitative and quantitative differences between our scenario and that of [29]. These are described in detail in Ref. [20].

For the case of Majorana fermions N_R , one can simply use the usual leptogenesis mechanism, with the scalars ϕ_\pm of our scenario playing the role of the usual scalars of the standard leptogenesis model [27]. The difference between the two models is that, in our scenario, the Yukawa couplings are real and CP violation is due to the phase difference in the initial conditions of the scalar fields.

There are several other ways of generating a lepton asymmetry in the context of our proposed mechanism. Also, as mentioned earlier, it is straightforward to have conventional baryogenesis via charged scalars. All of these scenarios will be discussed in Ref. [20].

4. Discussion and conclusions

In this Letter we have studied a mechanism for CP violation (originally proposed by Dolgov [8]) which is effective in the early Universe but could shut off at late times. A key feature of our mechanism is

that it does *not* involve any new CP-violating phases in the Lagrangian. Instead, in a model containing several scalar fields, initial conditions will lead to an asymmetry in the phases of these fields. CP-violating processes then arise as these quantum fields relax dynamically towards their symmetric ground state values. The initial displacement of these fields is completely natural in the context of early Universe cosmology.

There are many possible applications for this mechanism. In this Letter, we have concentrated on its contribution to leptogenesis and baryogenesis. Our calculation is applicable in the phase when the fields are rolling. This rolling phase will start when the Hubble constant drops to a value comparable to the mass of the scalar fields. It is at this time in the cosmological evolution that CP violation is most efficient. After the fields have relaxed to their vacuum values, our CP violation mechanism turns off. We plan to discuss more details, in particular applications to concrete baryogenesis models, in a future publication [20]. Note that string cosmology and brane world scenarios may provide natural settings for the origin of the scalar fields required for our mechanism (e.g. see Ref. [30] for a recent paper on how scalar fields from brane world scenarios can play a new role in spontaneous baryogenesis).

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